A Comparative Analysis of Cutting Forces in Precision Turning of Co-Cr-Mo Bio-implant Alloy in Dry and Wet Machining Environments

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Abstract: Decisive requirement for the long-term stability of the artificial joint is to minimize the release of debris particles. The wear/debris induced osteolysis and aseptic loosening are the result of failure of metal-on-metal joint implants. Severe plastic deformation (SPD) processes have been used to adapt the surface integrity properties by generating ultrafine or even nano-sized grains and grain size gradients in the surface region of work materials. These fine grained materials often show enhanced surface integrity properties such as wear resistance, corrosion resistance, fatigue life and improved functional performance compared with their predictable coarse grained counterparts. Metal-on metal bearings have a long history in total hip replacement. The experimental trials are planned according to Taguchi DOE in dry as well as in wet machining environments. It is shown that depth of cut is statistically significant on cutting force components and having dominating effect on radial and feed forces during precision turning of Co-Cr-Mo bio-implant alloy in dry machining environment. However, depth of cut and tool material both are statistically significant and show substantial effect on feed, radial and cutting forces in wet machining environment respectively. It is found that CBN insert gives better results in magnitudes of all cutting force components w.r.t. surface integrity therefore it is preferable to machine Co-Cr-Mo bio-implant alloy using CBN insert than any other tool materials.

Keywords: ***Co-Cr-Mo bio-implant alloy, Precision Turning, Wet and Dry machining, Cutting Forces, DOE and ANOVA***

1 Introduction

The most popular successful surgical treatments for patients suffering from arthritis and trauma is the arthroplasty (artificial joint replacement). On an average 1 million arthroplasties are performed annually worldwide [1]. At present, vivo metallic biomaterial used is the stainless steel followed by Ti (titanium) alloy and Co-Cr-Mo (cobalt–chromium–molybdenum) alloy [2-3]. Metal-on metal bearings have a long history in total hip replacement. In the past, total hip replacements (THR) involved the use of metal-metal Co-Cr-Mo alloys as the implant material, largely due to their relatively high strength, bio-compatibility and corrosion resistance. However, limitations in the manufacturing methods adversely affected the performance of these joints [4].

In addition, young patients with dynamic lifestyles undergoing total hip arthroplasty will require improved performance over a period of 30-40 years from now. Co-Cr-Mo alloy is the most suitable alloy often used in sliding parts, such as artificial hip and knee joints. When it is used in the head of an artificial joint, a mirrored finish is necessary to extend the life of the joint by compact abrasive wear and improved chemical stability. The search for a longer wearing behaviour has led to the development of metal on metal hip implants. These devices are commonly used today in patients less than 60 years of age [5-8]. Retrievals of Co-Cr-Mo metal-on-metal hip implants which did not experience seizing (some serviced in patients over 25 years) revealed little to no wear of the articulating surfaces. As a result, there is renewed interest on the optimization of the wear performance of Co-Cr-Mo metal-on-metal implants used in Total Hip Replacement (THR) [9]. To achieve the higher accuracy and surface finish using these processes, the available information of the process parameters is not adequate. Precision turning is one of the important process producing the higher accuracy and surface finish on metal implants [10].

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The recent review of key publications which emphasizes on studying the Co-Cr-Mo hip implants based on laboratory as well as clinical experiences is presented below.
Geetharani et al. described the surface morphology and wear behaviour of Co-Cr-Mo alloy by using polishing and coating methods (MPCVD) [1]. Author observed that "brain-coral" like surface morphology and rough surface morphology of 5 µm. Nevelos et al. tried to address the main metallurgical design issues in metal-on-metal bearing design [2]. Reclaru et al. reported that "inclusions" type microstructure was observed in electrochemical testing and polishing methods employed on Co-Cr-Mo alloy [3]. Howie et al. investigated twenty-four cobalt-chrome alloy McKee-Farrar matching acetabular and femoral components after 16 years in situ for wear and loss of sphericity [4]. The authors classified the wear on the components into four parts: polishing wear; fine abrasive wear; multidirectional dull abrasive wear and unidirectional dull abrasive wear.
Affatato et al. investigated the effect of surface profile parameters on amount of wear in metal artificial hip joints [5]. The surface roughness of the metallic ball heads was qualified in terms of average surface roughness Ra, total surface roughness Rt and skewness Rsk. The authors observed that all three parameters Ra, Rt and Rsk were capable of predicting the observed variability of the weight loss in a statistically significant way ($p < 0.01$).
Ohmori et al. observed the surface roughness (Ra) of 7 nm and also reported that surface roughness is superior to polished surface roughness [6]. Author used ELID grinding process in the experiments. Lee et al. found significant improvement in mechanical properties of Ni free Co-Cr alloy even under the as-cast condition [7]. The author investigated the hardness and tensile strength of Co-Cr-Mo alloy by preparing different chemical compositions and also used vacuum induction melting process for the experiments.
Grgazka et al. analyzed the influence of chosen modifiers on mechanical properties of composite materials on the base of Co-Cr-Mo alloy [8]. Young Chan et al. machined Co-Cr-Mo alloy using elliptical vibration cutting process [9]. A fine mirrored surface (with a maximum surface roughness under 25 nm P-V) was maintained up to a cutting length of about 14 m. Shu Yang et al. have done systematic experimental study to investigate the influence of different burnishing parameters on distribution of grain size, phase structure and residual stresses of the processed material [10]. The wear performance of the processed Co-Cr-Mo alloy was tested via pin-on-disk wear tests. Uddin et al. carried out machining trials on Co-Cr-Mo femoral heads and optimized the cutting parameters in finishing of femoral heads [11]. Author reported that the cutting speed, depth of cut and feed rate influenced surface roughness significantly, while both the feed rate and depth of cut were the dominant factors impacting the sphericity of femoral heads.
Cutting forces in turning influence machined surface and subsurface quality. Therefore, magnitudes of three cutting force components during dry and wet machining, viz. axial (feed) - Fa, tangential (cutting) - Ft and radial (thrust) - Fr were selected as in-process response variables. Very few literatures were reported regarding the measurement of cutting force components on Co-Cr-Mo bio-implant alloy.

2 Experimental Work

2.1 Process, Equipment and Tooling

Precision turning process is employed for investigation on surface integrity of Co-Cr-Mo bio implant alloy in dry and wet cutting environments. A production type CNC turning precision lathe (Model Jobber XL Make Micromatic) having spindle speed 5000 rpm and 13 KW capacity is used for conducting the experiments.
A Taguchi experimental design L9 orthogonal array is used for designing the parameter combinations for each experimental trial. In this orthogonal array, number of factors are 4 and number of levels are 3. Hence total numbers of runs are 9. The in-process response variables chosen are the magnitude of cutting force components during machining, viz. axial (feed) - Fa, tangential (cutting) - Ft and radial (thrust) - Fr on precision turning.
The input control factors selected for the experiments are: depth of cut (0.2-0.6-1 mm), feed rate (0.05-0.1-0.15 mm/rev), cutting speed (95-190-285 m/min) and cutting tool material (Ceramic-Carbide-CBN). Table 1 shows the experimental runs with the assigned factors to each of the columns of OA for precision turning process in dry and wet machining environments.
The work material used in the present investigation is bio-implant alloy, which is a low carbon wrought version of ASTM-F75 Co-Cr-Mo Alloy. A Co-Cr-Mo alloy bar (23 mm diameter) is used to prepare samples which have a diameter of 20 mm and a thickness of 10 mm.

Table 1 Experimental design L9 with actual factor values for precision turning

Expt. Run	Depth of cut (mm)	Cutting speed (m/min)	Feed (mm/rev)	Tool Material
1	0.2	95	0.05	Ceramic
2	0.2	190	0.1	Carbide
3	0.2	285	0.15	CBN
4	0.6	95	0.1	CBN
5	0.6	190	0.15	Ceramic
6	0.6	285	0.05	Carbide
7	1	95	0.15	Carbide
8	1	190	0.05	CBN
9	1	285	0.1	Ceramic

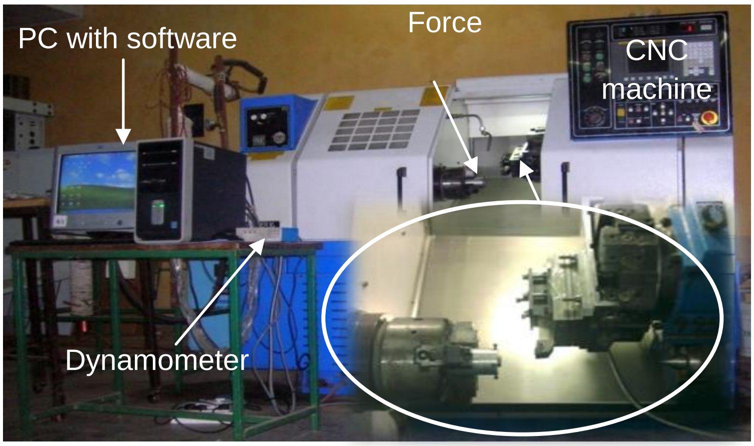

Fig. 1. Actual photograph of set up of cutting force measurements

2.2 Experimental Procedure

Initially nine workpieces to the required length from a long rod of Co-Cr-Mo were cut as substrates. These substrates are exactly made to size Ø20*10 mm thickness. An aluminium turning fixture is fabricated to hold these substrates having size of Ø50*120 mm length to facilitate holding of substrates during turning operation. Four screws are used to hold the substrate tight against the fixture. Fixture along with substrate is mounted on the three jaw chuck of the machine. After proper mounting pressure, fixture is trued properly for perfect rotation as shown in Fig. 1. To begin with a rough cut of 80 µm on substrate face is taken on each substrate and finish cut is taken on surface of 20 mm diameter. Finally each substrate is machined in dry and wet cutting environments as per the experimental trials given in Table 1. After each experiment the machined substrate is kept in a vacuum tight small container. During machining trials, the cutting forces were measured along with diametric cut of tool on workpiece. For measurement of all cutting forces KISTLER Model 9257A tool dynamometer is used along with CNC machine.

3 Results and Discussion

It is known that the quality of machined surfaces generated can be understood by analyzing the mechanics of machining, which involves analysis of cutting forces and the stresses involved in machining process. Therefore in this section analysis of cutting forces during machining of Co-Cr-Mo bio-implant alloy has been carried out. Fig. 2 shows the real time cutting force signals measured by tool dynamometer.

3.1 Statistical Analysis of Cutting Forces in Dry Machining Environment

The cutting force components were analysed using statistical methodology. ANOVA is used to discuss the significance of machining parameters. In addition, the effects of these parameters on the magnitude of cutting force components are analysed and described using MEPs.

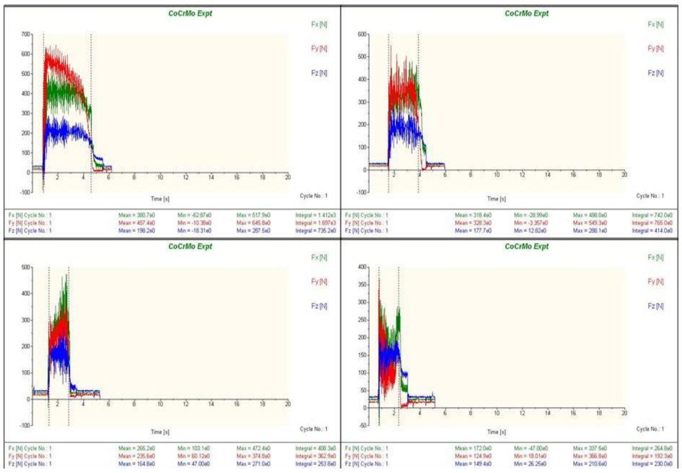

Fig. 2. Real Time Cutting Force Signals at different machining parameters

Table 2 ANOVA for (a) Feed Force, (b) Radial Force, and (c) Cutting Force in Dry Machining Environment

Source	DF	SS	MS	F	P	% Cont.
*Depth of cut, *d*	2	55687	27844	17.13	0.003	85.09
Feed, *f*	2	4933	2467	0.24	0.790	7.53
Cutting speed, *v*	2	2839	1419	0.14	0.875	4.33
Tool Material, *t*	2	1983	991	0.09	0.912	3.05
Residual error	0	-	-	-	-	-
Total	8	65442	-	-	-	-

*Statistically significant factor

(b) Radial force

Source	DF	SS	MS	F	P	% Cont.
*Depth of cut, *d*	2	26118	13059	9.73	0.013	76.42
Feed, *f*	2	218	109	0.02	0.981	@1
Cutting speed, *v*	2	1689	845	0.16	0.859	4.94
Tool Material, *t*	2	6148	3074	0.66	0.552	17.64
Residual error	0	-	-	-	-	-
Total	8	34173	-	-	-	-

*Statistically significant factor

(c) Cutting force

Source	DF	SS	MS	F	P	% Cont.
Depth of cut, *d*	2	29173	14587	3.77	0.087	55.66
Feed, *f*	2	2298	1149	0.14	0.874	4.38
Cutting speed, *v*	2	3075	1538	0.19	0.834	5.86
Tool Material, *t*	2	17865	8932	1.55	0.286	34.10
Residual error	0	-	-	-	-	-
Total	8	52411	-	-	-	-

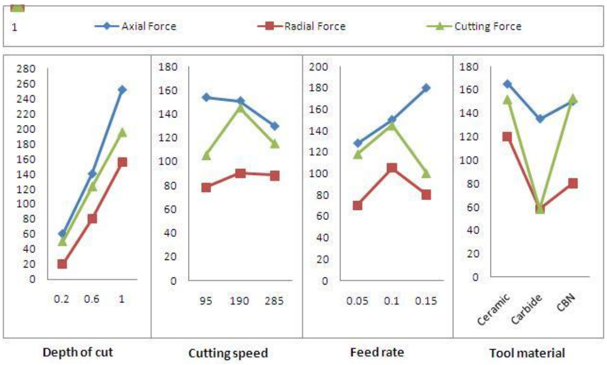

Fig. 3. MEPs for cutting force components in dry machining of Co-Cr-Mo Bio-implant alloy

It is observed from the ANOVA in Table 2 that the depth of cut is significantly influencing the feed force and radial force component at 95% statistical confidence level. It is known from the fundamentals of metal machining that the volume of material removal influences the cutting forces. As far as radial force component is concerned that the depth of cut is significantly influence at 95% statistical confidence level. In the case of cutting force component, none of the machining parameters influencing at 95% statistical confidence level. It is felt that the overall magnitude of cutting force may not get influenced because it acts less perpendicular to the chamfered cross-section on the cutting edge. The effect of machining parameters on the magnitude of cutting force components are described using MEPs (Fig. 3) in paragraphs below.

A. Effect of Depth of Cut on Cutting Forces

Depth of cut shows a linear trend on the magnitude of cutting force components. It is observed from MEPs that as depth of cut increases from 0.2 mm to 1 mm, it causes a considerable increase in the magnitude of feed forces, radial forces and cutting forces. The increase in cutting force magnitude could be a result of increased un-deformed chip cross sectional area due to increase in depth of cut. This could be due to decrease in the tool edge wear since the accumulated material around the cutting edge may be hard to cut and therefore shows higher magnitude.

B. Effect of Cutting Speed on Cutting Forces

It is observed from MEPs in Fig. 3 that when the cutting speed changes from 95 m/min to 190 m/min, the magnitude of radial and cutting force components increases in very small amount however the magnitude of feed force components decreases. This can be attributed to fact that as the cutting speed increases, an increase in temperature in the machining region could promote thermal softening causing ductility of work material to increase. As a result lower forces are required to shear the material during machining. Further, an increase in cutting speed from 190 m/min to 285 m/min, decreases the magnitude of cutting force in small amount.

C. Effect of Feed Rate on Cutting Forces

MEPs show that there is a linear trend in magnitude of feed force components as feed rate increases from 0.05 to 0.15 mm/rev. This trend follows the fundamental of metal machining that any increase in the feed rate increases the cross sectional area and the corresponding deforming volume. Therefore, increase in feed rate produces larger feed forces during machining. Also with an increase in feed rate from 0.05 mm/rev to 0.1 mm/rev, a sudden increase in radial and cutting forces is observed. However, the radial and cutting force components show a small decrease in their magnitude with increase in feed rate to 0.15 mm/rev.

D. Effect of Tool Material on Cutting Forces

It is observed that when the tool material is ceramic, large magnitudes of feed, radial and cutting force components are produced. Due to material hardness, it is quiet difficult to machine it from ceramic inserts and thus results in higher magnitude of cutting forces. It is also observed that there is a drastic reduction in magnitude of cutting forces when the insert material is carbide. However, when the CBN tool is used there is again increasing in magnitude of all forces is observed. This happened as the CBN is quiet harder than both inserts. Here's again harden ability of tool material plays a crucial role in machining of hard material too.

a. Statistical Analysis of Cutting Forces in Wet Machining Environment

The cutting force components were analysed using statistical methodology for wet machining environments. ANOVA is used to discuss the significance of machining parameters. In addition, the effects of these parameters on the magnitude of cutting force components are analysed and described using MEPs shown in Fig. 4.

Table 3 ANOVA for (a) Feed Force, (b) Radial Force, and (c) Cutting Force in Wet Machining Environment

Source	DF	SS	MS	F	P	% Cont.
*Depth of cut, *d*	2	51629	25814	6.90	0.028	69.70
Feed, *f*	2	7501	3750	0.34	0.726	10.12
Cutting speed, *v*	2	3216	1608	0.14	0.875	4.34
Tool Material, *t*	2	11725	5862	0.56	0.596	15.84
Residual error	0	-	-	-	-	-
Total	8	74071	-	-	-	-

*Statistically significant factor

(b) Radial force

Source	DF	SS	MS	F	P	% Cont.
*Depth of cut, *d*	2	43596	21798	10.26	0.012	77.38
Feed, *f*	2	2838	1419	0.16	0.856	5.03
Cutting speed, *v*	2	3840	1920	0.22	0.809	6.81
Tool Material, *t*	2	6066	3033	0.36	0.711	10.78
Residual error	0	-	-	-	-	-
Total	8	56340	-	-	-	-

*Statistically significant factor

(c) Cutting force

Source	DF	SS	MS	F	P	% Cont.
Depth of cut, *d*	2	17577	8789	0.51	0.622	14.63
Feed, *f*	2	2267	1133	0.06	0.944	1.88
Cutting speed, *v*	2	6629	3314	0.18	0.843	5.51
*Tool Material, *t*	2	93625	46813	10.61	0.011	77.98
Residual error	0	-	-	-	-	-
Total	8	120098	-	-	-	-

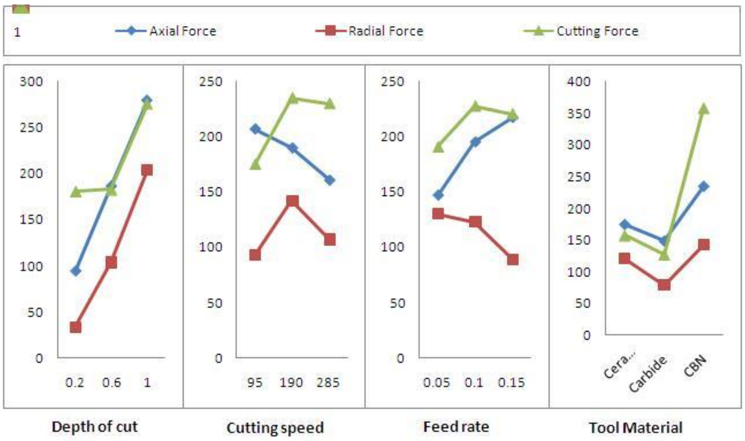

Fig. 4. MEPs for cutting force components in wet machining of Co-Cr-Mo Bio-implant Alloy

It is observed from the ANOVA in Table 3 that the depth of cut is significantly influencing the feed force and radial force component and tool material is statistically significant on cutting force at 95% statistical confidence level. It is known from the fundamentals of metal machining that the volume of material removal influences the cutting forces. As far as feed and radial force component is concerned that the depth of cut is significantly influence at 95% statistical confidence level. It is felt that the overall magnitude of cutting force may get influenced in wet machining environment. The effect of machining parameters on the magnitude of cutting force components are described using MEPs (Fig. 4) in paragraphs below.

A. Effect of Depth of Cut on Cutting Forces

Depth of cut shows a linear trend on the magnitude of radial and feed cutting force components while in non linear trend on the magnitude of cutting force component. It is observed from MEPs that as depth of cut increases from 0.2 mm to 1 mm, it causes a considerable increase in the magnitude of feed forces and radial forces. The increase in cutting force magnitude could be a result of increased un-deformed chip cross sectional area due to increase in depth of cut. This could be due to decrease in the tool edge wear since the accumulated material around the cutting edge may be hard to cut and therefore shows higher magnitude. However, there is some noise factor for small increment of cutting force component.

B. Effect of Cutting Speed on Cutting Forces

It is observed from MEPs in Fig. 4 that when the cutting speed changes from 95 m/min to 190 m/min, the magnitude of radial and cutting force components increases in very small amount however the magnitude of feed force components decreases in very small amount. This can be attributed to fact that as the cutting speed increases, an increase in temperature in the machining region could promote thermal softening causing ductility of work material to increase. As a result lower forces are required to shear the material during machining of hard materials. Further, an increase in cutting speed from 190 m/min to 285 m/min decreases the magnitude of all cutting forces in small amount.

C Effect of Feed Rate on Cutting Forces

MEPs show that there is increase in magnitude of feed and cutting force components as feed rate increases from 0.05 to 0.1 mm/rev. However, there is sudden decrease in radial force for same levels. This trend follows the fundamental of metal machining that any increase in the feed rate increases the cross sectional area and the corresponding deforming volume. Therefore, increase in feed rate produces larger feed forces during machining. Also with an increase in feed rate from 0.1 mm/rev to 0.15 mm/rev, a decrease in radial and cutting forces is observed. However, the feed force is increased in small amount due to sudden metal fracture at increased feed rate.

D Effect of Tool Material on Cutting Forces

It is observed that there is a non linear trend of different tool materials on all three cutting force components. When the tool material is ceramic, large magnitudes of feed, radial and cutting force components are produced like as in dry machining environment. Due to material hardness, it is quiet difficult to machine it from ceramic inserts and thus results in higher magnitude of cutting forces. It is also observed that there is a small reduction in magnitude of cutting forces when the insert material is carbide. However, when the CBN tool is used there is drastic increase in magnitude of all cutting forces is observed. This happened as the CBN is quiet harder than both inserts. Here's again harden ability of tool material plays a crucial role in machining of hard material results in higher magnitude of cutting forces.

4 Conclusions

Following conclusions can be drawn out on the influence of cutting forces in precision turning of Co-Cr-Mo bio-implant alloy in dry and wet machining environments.

- For dry machining environment the statistical analysis of factors influencing feed and radial forces shows that the depth of cut influences the magnitude of cutting forces to a great extent because it changes the volume and MRR at the tool nose radius.
- In wet machining environment that depth of cut show dominating effect on the magnitudes of feed and radial force components, whereas the factor tool material has nearly dominating effect on the magnitude of cutting forces.
- It is found tool material CBN gives better results in magnitudes of all cutting force components w.r.t. surface integrity therefore it is preferable to machine Co-Cr-Mo bio-implant alloy using CBN than any other tool materials.
- In the machining of Co-Cr-Mo bio-implant alloy, the magnitude of feed forces is quiet higher than that of other force components in dry machining environment. However, the magnitude of cutting force is larger than other force components in wet machining environment.

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References

[1]. Geetharani M, Nobu V, L D T Topoleski, 'Wear of sliding on carbide Co-Cr-Mo implant alloy', Technical Report, Arthritis Foundation, 2002.

[2]. Nevelos J., Shelton J. C. and Fisher J., 'Metallurgical considerations in the wear of metal-on-metal hip bearings', Hip International 14(1), 2004, 1-10.

[3]. L Reclaru, H Luthy, P Y Eschler, A. Blatter, O Loeffel and M H Zurcher, 'Cobalt-Chromium dental alloys enriched with precious metals', European cells and materials Vol. 7 suppl. 2, 2004, 51-52.

[4]. Howie D. W., McCalden R. W., Nawana N. S., Costi K., Pearcy M. J. and Subramanian, C., 'The long-term wear of retrieved McKee-Farrar metalon- metal total hip prostheses', Journal of Arthroplasty, 20(3), 2005, 350-357.

[5]. Affatato S., Bersaglia G., Yin J. Q., Traina F., Toni, A. and Viceconti M., 'The predictive power of surface profile parameters on the amount of wear measured in vitro on metal-on-polyethylene artificial hip joints', Proceedings of the Institution of Mechanical Engineers Part H-Journal of Engineering in Medicine, 220(H3), 2006, 457-464.

[6]. H Ohmori, K Katahira, Y Akinou, J Komotori and M Mizutani, 'Investigation on grinding characteristics and surface modifying effects of biocompatible Co-Cr alloy', Annals of CIRP, Vol. 55, 2006, 156-161.

[7]. S H Lee, N Nomura and A Chiba, 'Microstructures and mechanical properties of biomedical Co-Cr-Mo alloys with combination of N addition and Cr-enrichment', 1st Asian biomaterials congress, Dec. 6-8, 2007, Tsukuba, Japan.

[8]. Grgazka Dahlke M, Dabrowski JR, Dabrowski B, 'Modification of mechanical properties of sintered implant materials on the base of Co-Cr-Mo alloy', J Mater Process Technology, 2008, 199–205.

[9]. Young Chan Songa, Chun Hong Parka and Toshimichi Moriwaki, 'Mirror finishing of Co–Cr–Mo alloy using elliptical vibration cutting', Journal of Precision Engineering, 34, 2010, 784-789.

[10]. Shu Yang, 'Cryogenic Burnishing of Co-Cr-Mo Biomedical Alloy for enhanced Surface Integrity and improved wear Performance', PhD thesis, University of Kentucky, China, 2012.

[11]. M. S. Uddin, 'On the influence and optimization of cutting parameters in finishing of metallic femoral heads of hip implants', International Journal of Advanced Manufacturing Technology, (2014) 73:1523-1532.